

Robot-mediated haptic feedback outperforms vision in violin duo coordination

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Joint actions among humans rely on the integration of multiple sensory modalities, most notably auditory and visual cues, which support explicit communication between partners. However, haptic feedback provides a direct, implicit channel for sensorimotor communication, and its contribution to fine motor coordination in joint actions remains largely unexplored. Here, we demonstrate that haptic communication, rendered through bidirectionally coupled wearable robots, outperforms traditional auditory-visual feedback in a complex and challenging real-life joint action: ensemble violin performance. First, we developed a pair of two-degree-of-freedom upper-limb exoskeletons capable of transparently following violinists' natural movements and rendering viscoelastic torques proportional to the joint angular deviation between the partners. Then, we designed a within-subject experiment with 20 violin duos performing a musical piece under four sensory feedback conditions: auditory (A), auditory-visual (AV), auditory-haptic (AH), and auditory-visual-haptic (AVH), across two tempi (72 and 100 beats per minute). Despite the musicians being unfamiliar with the robot-mediated haptic feedback and unaware of the bidirectional connection between them, haptic feedback (AH and AVH) substantially enhanced spatiotemporal coordination and dynamic musical alignment compared with the extensively trained auditory-visual feedback (A and AV). The multisensory feedback condition AVH yielded the highest scores across all measures. Our findings demonstrate that haptic feedback can support fine motor coordination in violin duo performance more effectively than visual cues, particularly for professional musicians, because of its implicit and embodied nature, and that it can be effectively delivered via wearable robots, expanding the paradigms of human-human sensorimotor interactions.

INTRODUCTION

Joint actions are coordinated activities between individuals to achieve a shared goal and are fundamental to many forms of human interaction and collaboration (1). Many common joint actions rely on physical interaction and span a wide spectrum (2) from simple tasks, such as handing a glass to a friend or moving a table together, to complex activities, such as teaching a child how to walk or assisting a patient in motor recovery. In these contexts, haptic communication is essential: Forces and motion are exchanged either through jointly manipulated objects or through direct physical contact with a partner's limbs (3). From early childhood development, humans learn to perceive, interpret, and respond to others' forces and motion, thereby developing intricate sensorimotor communication strategies (4, 5).

In recent years, systematic research on joint action involving haptic feedback has demonstrated that physically interacting partners exchange a conspicuous amount of sensory information through haptic communication (6–8). This information includes motion intention (9), the partner's goal (10), task-specific roles (11, 12), and

execution timing (13) and is used to predict the partner's future actions, optimize one's own motor control, and enhance interpersonal coordination, ultimately leading to improved joint performance (14). To investigate these mechanisms, previous studies have either directly coupled two individuals manipulating a shared object and measuring the interaction forces (7, 8, 15, 16) or adopted technological solutions to create a virtual coupling between them, such as using end-effector robots to measure and replicate the forces exchanged between partners (17). In such paradigms, two individuals interact with separate robotic devices that are programmed to transmit forces to one another, rendering bidirectional haptic feedback through viscoelastic force fields. This approach, commonly referred to as physical human-robot-human interaction (18), has been applied in a variety of experimental tasks (19, 20), including point-to-point reaching (7, 21); shared virtual object manipulation (22, 23); and tracking tasks with one (12, 24, 25), two (14, 26), or three (27) degrees of freedom (DoFs). Across these studies, robot-mediated haptic feedback has been shown to improve joint performance compared with solo performance when partners' skill sets are balanced (7, 11) or artificially unbalanced (10, 14, 27).

These findings have not only extended the evidence on the role of haptic feedback in individual performance (28–30) but also demonstrated its potential to uncover sensorimotor mechanisms underlying joint action and to promote alternative ways of enhancing performance. However, most studies on robot-mediated haptic communication have been conducted in highly simplified, laboratory-controlled settings and have rarely implemented the ecological complexity of real-life interactions (3, 19). Even studies involving dual robotic interfaces have traditionally used end-effector robots in tasks with constrained spatial and temporal dynamics, such as following predefined

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trajectories (10, 14) or performing movements with a fixed timing (21). Recent works have started exploring more complex forms of haptic coupling by using wearable robots but were implemented in similarly structured and constrained tasks, such as tracking a moving target with stationary upper-limb exoskeletons (31, 32) or performing cyclic movements with lower-limb exoskeletons, like walking at fixed speed (33) and sit to stand (34). Although these contributions have been instrumental in advancing our understandings, it remains unknown whether the benefits observed in controlled tasks extend to more dynamic, naturalistic, and unstructured joint tasks (13, 19). Here, we aimed to address these questions by presenting the implementation of robot-mediated haptic coupling in a real-world joint action task, using connected wearable robots to study how interpersonal coordination unfolds in the presence of haptic feedback.

Recently, ensemble music performance has emerged as a promising domain for investigating ecologically valid joint action (3, 35), because musicians act as dynamic agents who continuously exchange information through complex sensorimotor coordination strategies to achieve a shared artistic goal. Several studies have confirmed that the key mechanisms of interpersonal coordination identified in simplified visuomotor tasks are also present in musical settings (36, 37). Traditional ensemble music performance lacks direct physical interaction, as opposed to other artistic forms like dancing, and musicians rely almost exclusively on explicit communication channels, such as auditory and visual channels, to coordinate (37–40). Therefore, through years of intensive training, musicians develop sophisticated cognitive, motor, and social skills, including predictive models and adaptive control mechanisms, that allow them to dynamically react to changes in tempo, expressive gestures, and synchronization demands (41) and achieve smooth and cohesive ensemble performance (36, 42, 43). Auditory cues are the primary basis for temporal alignment and allow musicians to coordinate with the rhythmic and expressive structure of the piece while accommodating deviations or errors (38, 42, 44, 45). When auditory information is disrupted, such as during tempo changes or at the onset of a piece, visual cues capturing gestural dynamics play a crucial complementary role (44, 46–49). Musicians' body movements encode essential information about tempo and rhythm, with features such as velocity, acceleration, and gesture duration providing predictive cues for synchronization (50–52). Visual feedback is therefore crucial in ensemble performance to exchange motion-related information, and, in the absence of direct physical contact, it remains the only available channel for such communication. Despite offering high spatial resolution, visual feedback is generally slower than haptic feedback (28, 53, 54), and this feature could limit its benefits in such temporally demanding tasks. This limitation raises a fundamental question: Could haptic feedback, being an implicit sensory modality, offer a more immediate, embodied, and effective communication channel for facilitating interpersonal coordination between partners? Technological constraints have long prevented the exploration of this possibility in ecological contexts such as ensemble music performance. Yet, investigating this hypothesis could help to better understand the sensorimotor mechanisms underlying joint action and open avenues for enhancing interpersonal coordination. To address this gap, we embraced the challenge of studying a considerably complex and ecologically valid joint task: violin playing in a duo. This task demands fine motor control and seamless multi-sensory integration, traditionally based on auditory and visual cues.

Here, we investigated whether haptic feedback could serve as an effective communication channel to enhance performance and

coordination in violin duos. To test this hypothesis, we required a robotic system capable of delivering meaningful haptic feedback while minimally perturbing the natural execution of an extraordinarily delicate task. We developed two replicas of a custom-powered upper-limb exoskeleton designed to render bidirectional haptic feedback at the shoulder and elbow joints (Fig. 1 and Movie 1). Each exoskeleton measured the joint angular trajectories of a musician and rendered torques proportional to the difference with the other musician's trajectories through stiffness and damping coefficients. This control strategy created a viscoelastic torque field that mechanically coupled the musicians' movements, providing haptic information about each other's positions, thereby simulating direct physical contact between their limbs. Then, we designed an experiment involving violinist dyads performing under different sensory feedback conditions, including auditory, visual, and haptic feedback, and investigated how these influenced the interpersonal coordination. Our findings suggest that exoskeleton-mediated haptic interactions are more effective than visual cues in complementing auditory feedback and eliciting kinematic and acoustic coordination between violinists. These results unlock the potential of using a powerful, previously unexplored sensorimotor channel that enables more accurate, responsive, and embodied interpersonal coordination by physically coupling individuals. Our work extends the paradigm of physical human-robot-human interaction from simplified, laboratory-controlled tasks to complex, ecological scenarios and establishes a foundation for next-generation haptic augmentation in collaborative human tasks.

RESULTS

To evaluate the effects of haptic feedback on interpersonal coordination, we conducted an experiment involving 20 violinist dyads (10 amateurs and 10 professionals) who performed a custom musical piece (Fig. 2B) across four sensory feedback conditions—auditory only (A), auditory-visual (AV), auditory-haptic (AH), and auditory-visual-haptic (AVH)—at two tempi [72 and 100 beats per minute (bpm)] (Fig. 2D), with each condition repeated three times for each tempo. In the haptic conditions (AH and AVH), the exoskeletons delivered real-time torques on the basis of the joint angular difference between partners, generating a soft-moderate coupling by rendering noticeable but noncoercive haptic cues, whereas, in the nonhaptic conditions (A and AV), they only compensated for friction and inertia. Across all sensory feedback conditions, musicians could always hear each other's performance; in the visual conditions (AV and AVH), they could also see each other, whereas, in the nonvisual conditions (A and AH), visual contact was prevented by a curtain. Moreover, musicians were blinded to the origin of the haptic cues and to the condition being tested. The randomization of sensory feedback conditions and tempi ensured the minimization of adaptation effects throughout the experiment (see Supplementary Methods). Last, before and after the sensory feedback conditions, dyads performed the musical piece in conventional settings, namely, without the exoskeletons and with auditory and visual feedback (baseline, BL, and posttest, PT, assessments).

We quantified the spatiotemporal coordination between the musicians both in the task space (moving the bow on the strings) and in the joint space (managing the redundancy of the upper limb to produce similar interlimb coordination) (Fig. 3A). Bow coordination was assessed by tracking the position of each bow relative to its violin, extracting principal components using principal components analysis (PCA), and computing spatial coordination as the mean

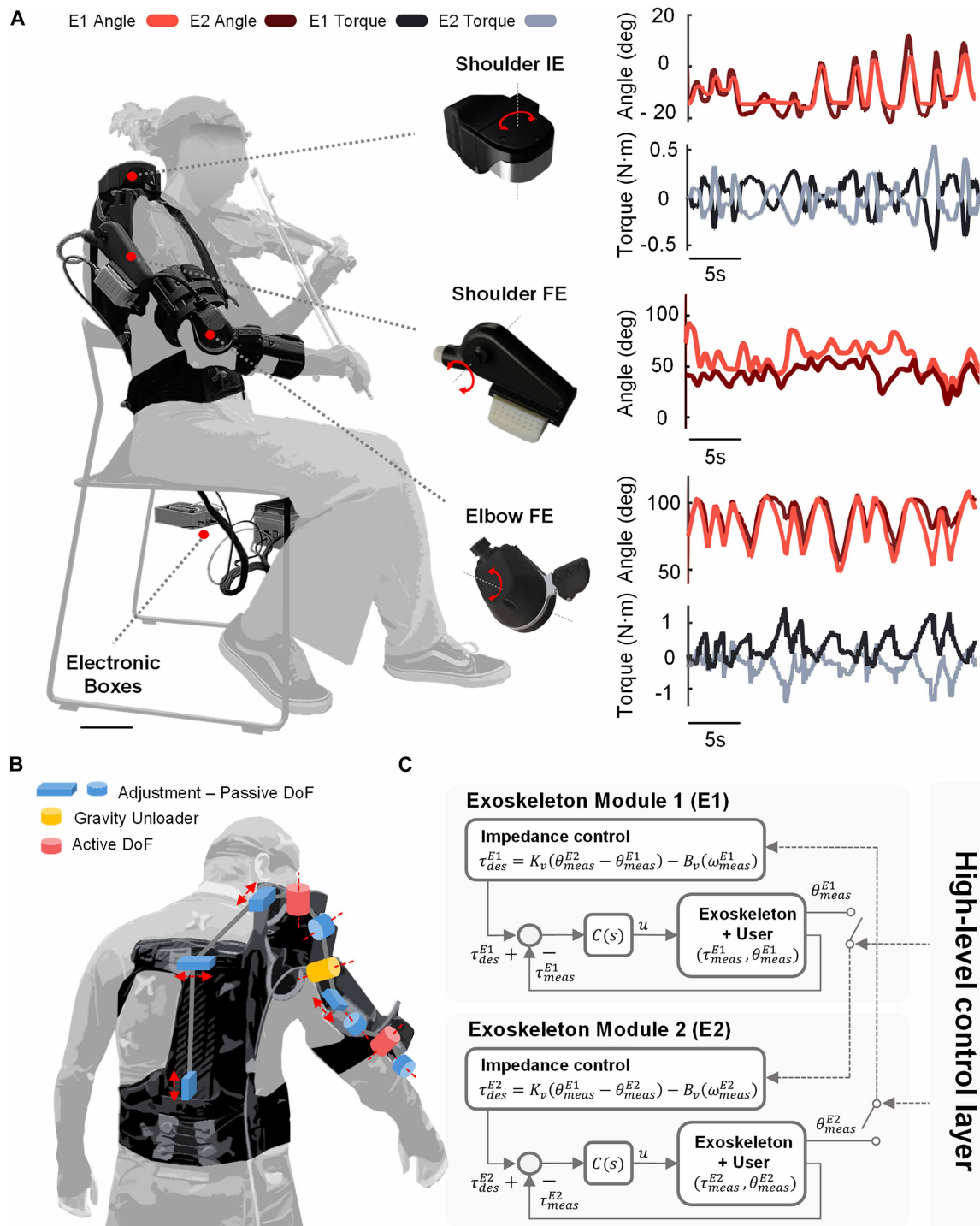


Fig. 1. Overview of the exoskeletons. (A) Main components of the system, including the shoulder internal-external rotation (IE) and elbow flexion-extension (FE) active modules with the corresponding measured joint angles and torques and the passive shoulder flexion-extension (FE) module with the measured joint angle. deg, degrees. **(B)** Control layers, implemented as distributed systems in two electronic boxes, include a middle-level control to render the viscoelastic behavior at the actuated joints. Two working modalities are implemented: NI, where the system is set in TM, and BI, where the reciprocal partner's trajectories are used as reference. **(C)** Actuators and the passive unloader are housed in 3D-printed parts attached to a carbon fiber T-shaped frame. The active components are linked via a lockable hinge that sets the pose of the passive shoulder gravity compensator. The exoskeleton is attached to the user's body at three main points: a semirigid lumbar belt, a trunk cross-strap, and arm and forearm cuffs, all secured with Velcro straps for easy donning or doffing and adaptability to various body types. The passive internal-external rotation joint connects the shoulder and elbow modules, allowing a decoupling of their movements.

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Movie 1. Summary of the study design and findings. This movie shows how exoskeletons can be used to create a virtual physical coupling between violinists, allowing them to feel each other's movements in real time. We show that this robot-mediated haptic feedback is more effective than traditional visual feedback in enhancing kinematic coordination and musical alignment.

absolute error between the violinists' principal components and temporal coordination as the relative phase of the Hilbert-transformed signals. Joint coordination was evaluated by extracting joint angles and applying partial least-squares correlation (PLSC) to identify the most strongly covarying components between partners. Spatial coupling was calculated as the Euclidean distance between these components, and temporal coupling was calculated as Pearson's correlation coefficient. As defined here, bow and joint spatial coordination corresponds to the average error between the dominant components of the movements; thus, lower values indicate higher spatial coordination. In contrast, bow and joint temporal coordination reflects the temporal correlation between the dominant components; thus, higher values represent stronger temporal coordination (additional details in Supplementary Methods). Additionally, we verified the robustness of the results by adopting an alternative approach based on canonical correlation analysis (see Supplementary Methods and fig. S1).

To test the effects of the experimental factors, we used generalized linear mixed models, with expertise (amateurs and professionals), tempo (72 and 100 bpm), and condition (A, AV, AH, AVH, BL, and PT) as fixed effects and dyad as a random effect. A significant main effect of condition emerged for both spatial ($F_{5,540} = 66.05$, $P < 0.001$) and temporal ($F_{5,540} = 18.17$, $P < 0.001$) bow coordination, whereas expertise did not show any significant main effects. Nonetheless, a significant interaction with the condition was observed for both spatial ($F_{5,540} = 5.562$, $P < 0.001$) and temporal ($F_{5,540} = 3.154$, $P = 0.008$) coordination. Similarly, the condition significantly affected both spatial ($F_{5,540} = 78.16$, $P < 0.001$) and temporal ($F_{5,540} = 23.94$, $P < 0.001$) joint coordination, whereas neither expertise nor tempo had significant main effects. A significant interaction between expertise and condition emerged for spatial ($F_{5,540} = 2.67$, $P = 0.021$) and temporal ($F_{5,540} = 2.423$, $P = 0.035$) joint coordination. For brevity, effect sizes (Cohen's $|d|$) and 95% confidence intervals (CIs) are reported only for statistically significant contrasts (full results are provided in tables S2 to S10).

Haptic feedback enhances coordination compared with visual feedback

Haptic feedback (AH and AVH) consistently improved spatiotemporal coordination compared with traditional sensory modalities (A and AV) across most of the coordination metrics. For spatial bow coordination (Fig. 3D), amateurs and professionals performed significantly better in AH and AVH than in A and AV. Coordination improved by 23% in AH [$P < 0.001$, $d = 0.93$, 95% CI (0.61, 1.38)] and by 33% in AVH [$P < 0.001$, $d = 1.26$, 95% CI (0.86, 1.84)] compared with A and by 15% in AH [$P < 0.001$, $d = 0.58$, 95% CI (0.33, 0.90)] and by 24% in AVH [$P < 0.001$, $d = 0.91$, 95% CI (0.62, 1.32)] compared with AV, although the improvement in AH was not significant for amateurs ($P = 0.088$). Results for temporal bow coordination (Fig. 3E) followed a similar pattern: Improvements relative to A reached 7% in AH [$P < 0.001$, $d = 0.69$, 95% CI (0.38, 1.1)] and 11% in AVH [$P < 0.001$,

$d = 1.15$, 95% CI (0.75, 1.71)], whereas they were more modest compared with AV and only significant for professionals in AVH [$P < 0.001$, $d = 0.65$, 95% CI (0.37, 1.04)].

Joint-level metrics confirmed this pattern: Both amateurs and professionals achieved significantly better spatial coordination compared with A by 20% in AH [$P < 0.001$, $d = 0.79$, 95% CI (0.52, 1.17)] and by 25% in AVH [$P < 0.001$, $d = 0.96$, 95% CI (0.63, 1.41)], and improvements were also found compared with AV, with a 13% increase in AH [$P < 0.001$, $d = 0.53$, 95% CI (0.30, 0.83)] and an 18% increase in AVH [$P < 0.001$, $d = 0.69$, 95% CI (0.44, 1.04)] (Fig. 3B). Similarly, musicians achieved better temporal joint coordination in AH and AVH: Compared with A, coordination improved by 6% in AH [$P < 0.001$, $d = 0.78$, 95% CI (0.44, 1.25)] and by 9% in AVH [$P < 0.001$, $d = 1.10$, 95% CI (0.70, 1.66)], whereas, compared with AV, coordination significantly improved for both amateurs and professionals by 5% in AVH [$P < 0.001$, $d = 0.72$, 95% CI (0.46, 1.08)] but significantly only for professionals in AH [$P = 0.006$, $d = 0.52$, 95% CI (0.20, 1.02)] (Fig. 3C).

To separate the specific contribution of visual feedback, we directly compared visual and nonvisual conditions (AV versus A and AVH versus AH). Results showed that, overall, amateurs achieved significantly better spatiotemporal coordination in AV compared with A and that, for both groups, AVH was better than AH, significantly for spatial bow coordination [$P < 0.001$, $d = 0.37$, 95% CI (0.21, 0.58)]. Overall, these results confirm the key role of visual feedback in supporting spatiotemporal coordination, given that condition AV outperformed condition A and condition AVH outperformed condition AH. However, the results also show that replacing traditional visual cues with haptic feedback enhances spatiotemporal coordination, especially for professionals (fig. S2 shows a highlight of the AV-AH contrasts for amateurs and professionals), despite participants consistently rating their performance higher when they could see each other (fig. S3; additional details about participants' subjective perspective are provided in Supplementary Methods). Only 13 of 40 participants

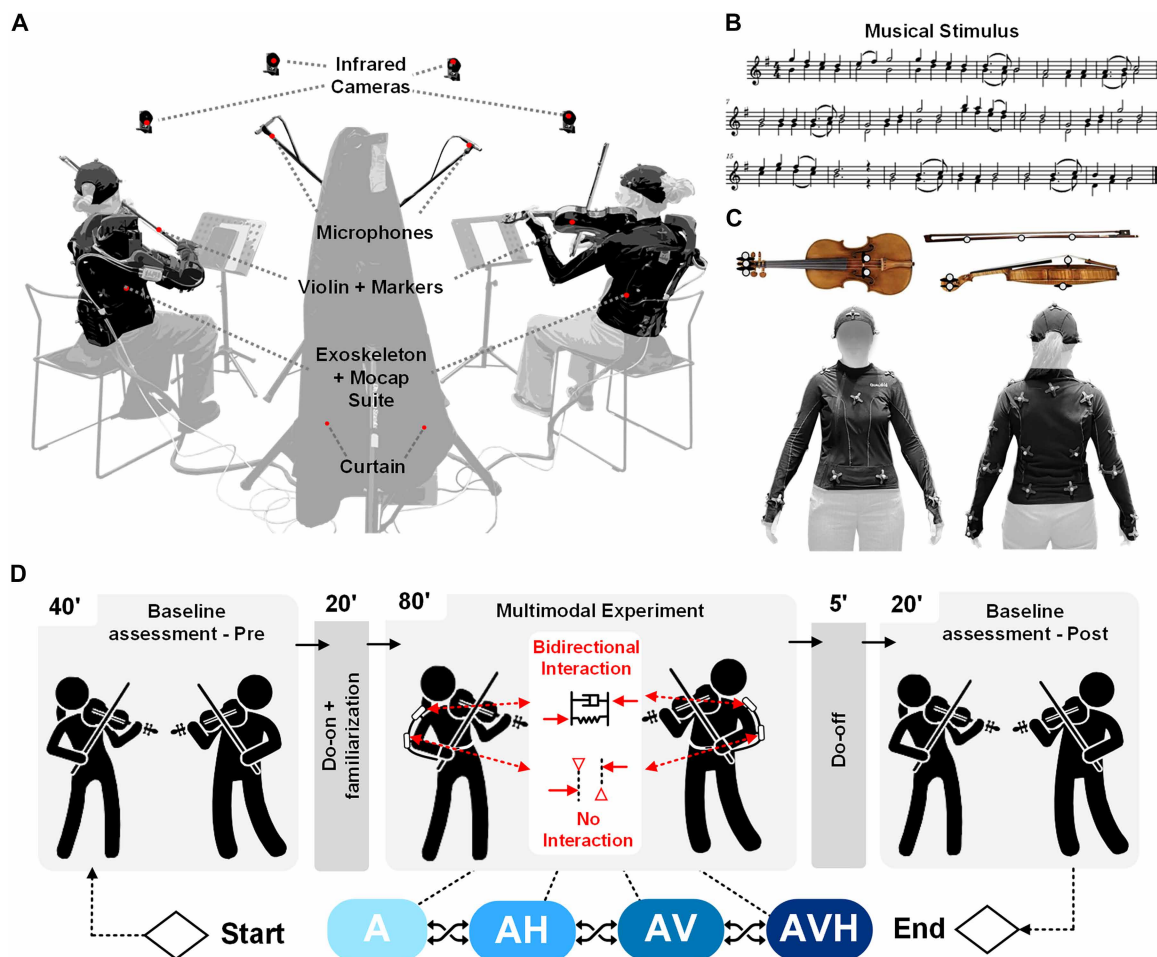


Fig. 2. Overview of the experimental setup. (A) Participants wearing MoCap suits and exoskeletons were seated next to each other separated by a curtain, adjusted as needed according to the tested experimental condition. (B) Musical stimulus composed for the experiment and played at two different tempi (72 and 100 bpm). (C) Infrared marker position on the participants. (D) Schematic representation of the experimental protocol with randomized sensory feedback conditions: A, AV, AH, and AVH (each condition was repeated three times for each tempo). Before and after the six experimental blocks, dyads performed the piece twice in a traditional configuration (auditory-visual feedback, no exoskeletons).

correctly identified the partner as the source of the haptic torques, suggesting that the feedback was largely implicit.

The combination of haptic feedback with AVH consistently produced the highest levels of coordination, minimizing spatial and temporal discrepancies between partners, particularly for professionals. To ensure that the observed performance improvements in haptic conditions (AH and AVH) compared with transparent conditions (A and AV) were specifically attributable to the haptic feedback rather than unintended interference from the exoskeletons, we examined the accuracy of torque rendering and verified that the magnitude of the haptic torques was sufficient to provide meaningful haptic cues without constraining the movements (see Supplementary Methods and tables S11 and S12).

Haptic feedback outperforms traditional auditory-visual coordination without exoskeletons

Spatiotemporal coordination in the haptic conditions was consistently superior to the no-exoskeleton conditions (BL and PT). Regarding spatial bow coordination (Fig. 3D), both AH and AVH

significantly outperformed BL and PT regardless of expertise. Compared with BL, coordination improved by 22% in AH [$P < 0.001$, $d = 0.75$, 95% CI (0.34, 1.27)] and by 32% in AVH [$P < 0.001$, $d = 1.02$, 95% CI (0.58, 1.61)], and improvements relative to PT were similarly robust, with increments of 18% in AH [$P < 0.001$, $d = 0.67$, 95% CI (0.36, 1.08)] and 28% in AVH [$P < 0.001$, $d = 0.97$, 95% CI (0.62, 1.46)]. Temporal bow coordination was modulated by expertise (Fig. 3E): Amateurs showed significant improvements relative to BL in both AH by 11% [$P < 0.001$, $d = 0.70$, 95% CI (0.10, 1.73)] and AVH by 16% [$P < 0.001$, $d = 1.00$, 95% CI (0.24, 2.10)], whereas professionals performed similarly (+2% and +6%, $P > 0.2$). When compared to PT, both groups achieved similar temporal bow coordination.

The same pattern was observed at the joint level: Improvements in spatial joint coordination (Fig. 3B) relative to BL reached 26% in AH [$P < 0.001$, $d = 0.88$, 95% CI (0.47, 1.43)] and 31% in AVH [$P < 0.001$, $d = 1.01$, 95% CI (0.58, 1.59)], and similar results were observed compared to PT [AH: +24%, $P < 0.001$, $d = 0.96$, 95% CI (0.63, 1.44); AVH: +29%, $P < 0.001$, $d = 1.13$, 95% CI (0.75, 1.66)]. For temporal joint coordination, amateurs again showed significant

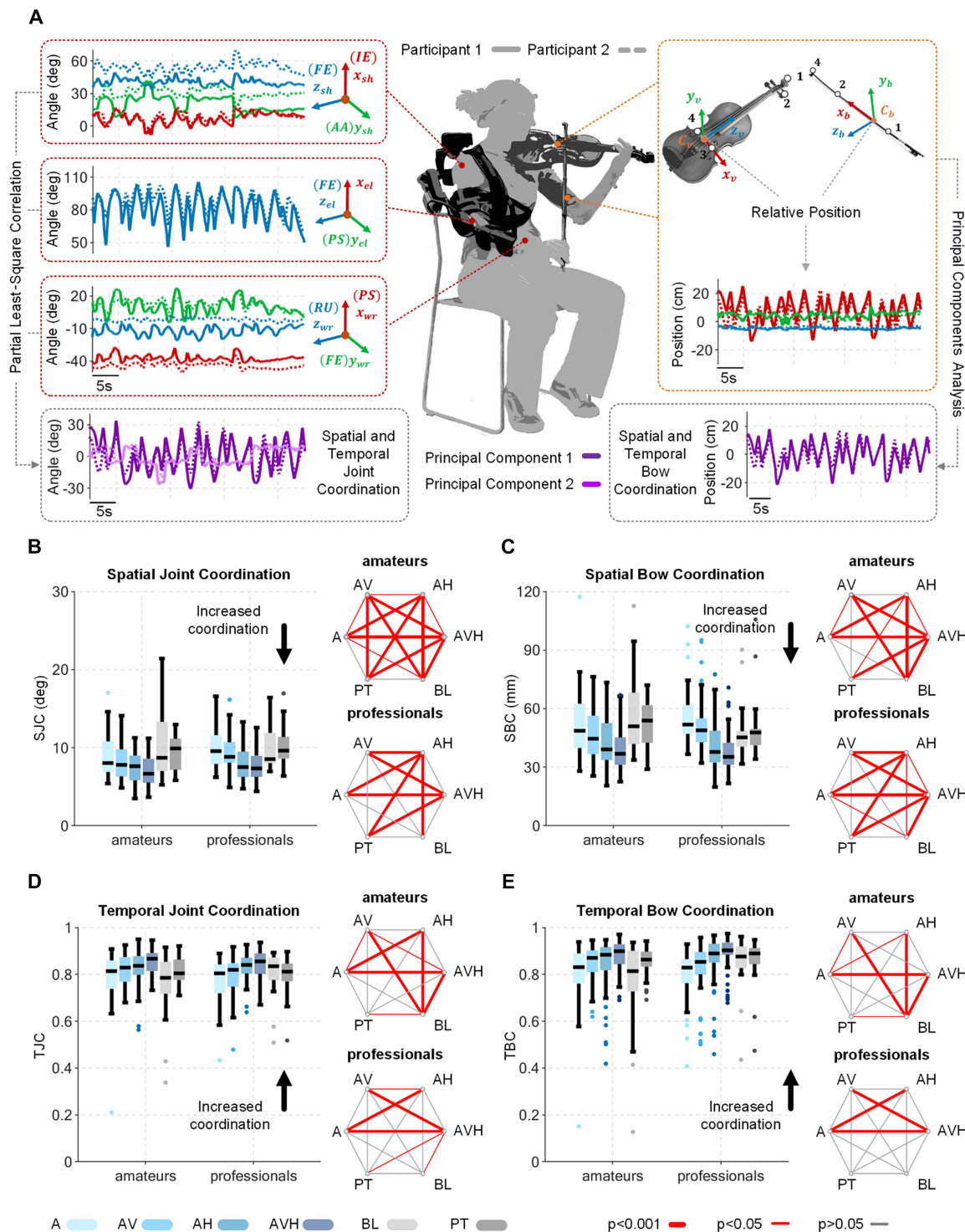


Fig. 3. Spatiotemporal joint and bow coordination under different feedback conditions. (A) Schematic diagram of the estimation of spatial and temporal joint and bow coordination. Spatiotemporal joint coordination was estimated using PLSC on the right upper limb joint angles (shoulder, elbow, and wrist), whereas spatiotemporal bow coordination was estimated using PCA on the relative positions of the bow centroid relative to the violin centroid, for each member of the dyads. (B to E) Box plots of spatial and temporal coordination for joints [(B) and (C)] and bow [(D) and (E)] in the different experimental conditions for amateur and professional violinists. The horizontal lines in the box plots show the medians, the box limits represent the 25th and 75th percentiles, and the whiskers extend to the maximum and minimum data points. For the four sensory feedback conditions (shades of blue), $n = 60$ (10 dyads per group, six repetitions per condition); for the two no-exoskeleton conditions (shades of gray), $n = 20$ (10 dyads per group, two repetitions per condition). Statistical significance in the pairwise comparisons is reported in the gray hexagons, and red connections indicate a statistically significant difference (thick red lines, $P < 0.001$; thin red lines, $P < 0.05$).

improvements relative to BL in both AH [$P < 0.001$, $d = 0.71$, 95% CI (0.06, 1.60)] and AVH [$P < 0.001$, $d = 0.82$, 95% CI (0.37, 1.39)], for which similar improvements were found for professionals. Conversely, amateurs achieved similar coordination relative to PT in both AH and AVH, whereas professionals showed a significant improvement in AVH [$P = 0.006$, $d = 0.71$, 95% CI (0.25, 1.41)]. These results confirm that the introduction of haptic feedback significantly enhanced spatiotemporal coordination, regardless of expertise, beyond the traditional auditory-visual coordination in the no-exoskeleton conditions.

To assess the effects of the presence of the exoskeletons, we directly compared the transparent mode conditions (A and AV) with the no-exoskeleton conditions. Amateurs generally improved their coordination in A and AV compared with BL and performed similarly or better than in PT, whereas professionals achieved similar or worse coordination in A and AV compared with BL and PT. These results suggest that playing with exoskeletons in transparent mode (A and AV) led to different outcomes depending on expertise: Amateurs improved their spatiotemporal coordination compared with BL and performed similarly to PT, whereas professionals generally performed similarly or worse, particularly in condition A.

Haptic feedback enhances dynamic alignment

To evaluate whether haptic feedback and exoskeleton use influenced the acoustic quality of violin performance, we analyzed two audio-based parameters: spectral brightness, indexed by the spectral centroid and associated with timbre and bow pressure (55, 56), and dynamic alignment, defined as the temporal synchronization of loudness changes [root mean square (RMS) amplitude] between players (Fig. 4). Additionally, to control for acoustic artifacts introduced by the curtain used to remove visual feedback (see Materials and Methods), comparisons were restricted to conditions recorded under identical acoustic setups: A versus AH, AV versus AVH, and no-exoskeleton conditions (BL and PT) versus AV and AVH. This approach minimized the influence of environmental confounds, such as sound reflections or dampening, on alignment measures.

Linear mixed models with expertise, tempo, and condition as fixed effects and with dyad as a random effect revealed robust effects on dynamic alignment. Significant main effects of condition and expertise were found when comparing A-AH (condition: $F_{1,214} = 49.62$, $P < 0.001$; expertise: $F_{1,18} = 14.67$, $P = 0.001$) and AV-AVH (condition: $F_{1,212} = 50.43$, $P < 0.001$; expertise: $F_{1,18} = 6.56$, $P = 0.020$). Specifically, the addition of haptic feedback consistently improved alignment both

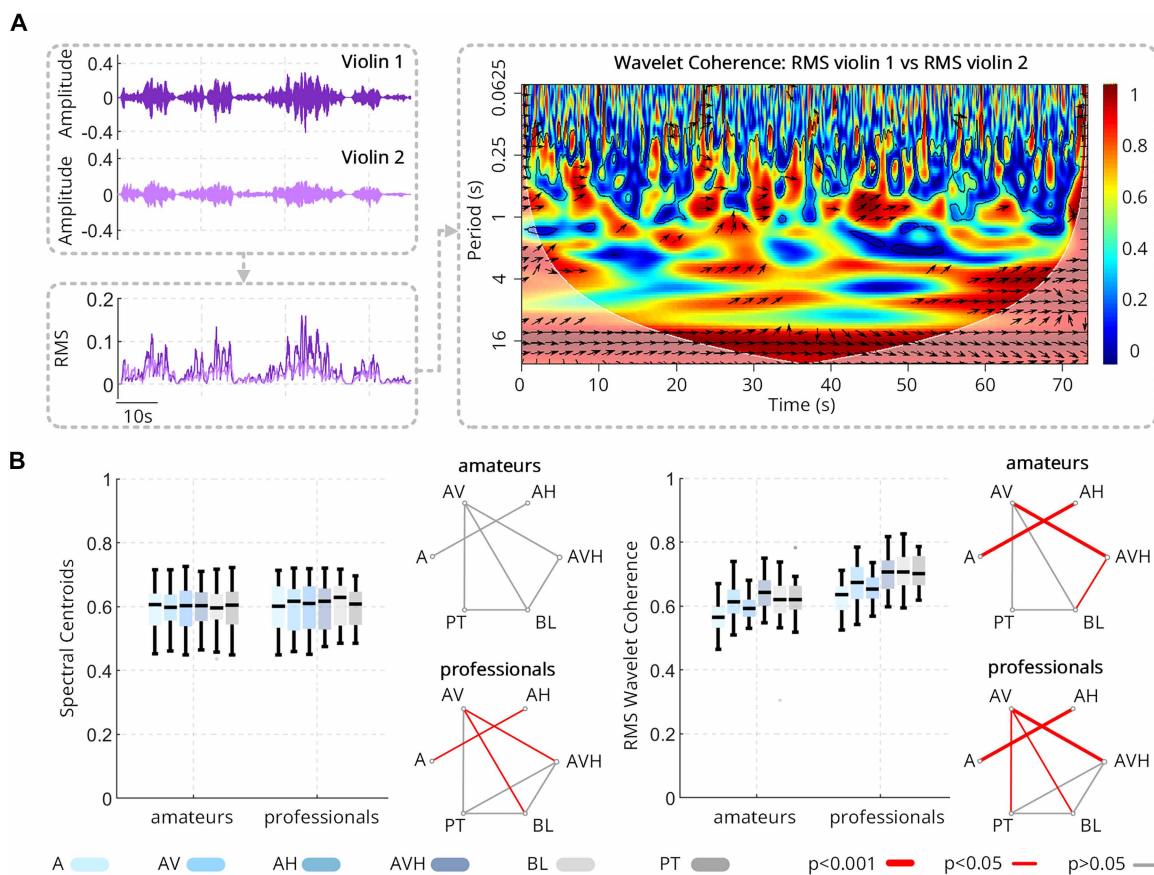


Fig. 4. Results for the acoustic features of produced sound. (A) Brightness and loudness of the sound were estimated from the spectral centroid and RMS of the wavelet coherence for each member of the dyad. (B) The horizontal lines in the box plots show the medians, the box limits represent the 25th and 75th percentiles, and the whiskers extend to the maximum and minimum data points. For the four sensory feedback conditions (shades of blue), $n = 60$ (10 dyads per group, six repetitions per condition); for the two no-exoskeleton conditions (shades of gray), $n = 20$ (10 dyads per group, two repetitions per condition). Statistical significance in the contrasts between conditions is reported in the gray hexagons, red connections indicate a statistically significant difference (thick red lines, $P < 0.001$; thin red lines, $P < 0.05$), and light gray connections represent contrasts not included in the analysis because of confounding factors (conditions without visual feedback included a curtain that may have influenced the audio recordings compared with visual feedback conditions).

in nonvisual conditions, with AH being significantly higher than A [$P < 0.001$, $d = 0.91$, 95% CI (0.66, 1.16)], and in visual conditions, with AVH being significantly higher than AV [$P < 0.001$, $d = 0.92$, 95% CI (0.67, 1.17)]. Similar effects were found when comparing visual conditions with (AV and AVH) and without the exoskeletons (BL and PT) at 72 bpm, and a significant interaction of condition and expertise emerged ($F_{3,172} = 3.73$, $P = 0.012$). Specifically, professionals showed higher alignment both in BL [$P = 0.013$, $d = 0.90$, 95% CI (0.33, 1.46)] and PT [$P = 0.045$, $d = 0.78$, 95% CI (0.21, 1.35)] compared with AV, whereas no significant differences were found with AVH; conversely, amateurs showed higher alignment in AVH compared with BL [$P = 0.027$, $d = 0.83$, 95% CI (0.27, 1.40)] but not relative to PT. Last, professionals generally demonstrated significantly higher alignment than amateurs [$P = 0.006$, $d = 1.67$, 95% CI (0.63, 2.71)].

We adopted a similar approach to investigate the effects on spectral brightness. No significant main effects of conditions and expertise were found when comparing A-AH and AV-AVH, but a significant interaction emerged in both cases, indicating that the effect of haptic feedback on spectral brightness differed between professionals and amateurs. Specifically, professionals showed increased spectral brightness in the haptic conditions compared with the nonhaptic conditions, whereas this effect was absent for amateurs. The full model summaries of the statistical analyses for the audio features are reported in tables S13 to S24.

DISCUSSION

This study demonstrates that robot-mediated haptic feedback is more effective than visual cues in enhancing interpersonal coordination in joint musical performance, particularly for professional musicians and across most coordination metrics. Previous research has shown that haptically coupling individuals through end-effector robots enhances multisensory integration, allowing individuals to use the partner's information to better estimate their movement errors and refine the motor control accordingly (10, 14, 27). We extended this concept beyond simple, structured laboratory tasks to a complex and challenging real-life application: violin duo performance. This activity requires not only a highly refined and specialized motor repertoire but also extensive use of multisensory integration to achieve precise coordination. To demonstrate the effectiveness of haptic feedback, we used a pair of exoskeletons that delivered accurate haptic cues directly at the musicians' upper-limb joints without introducing disturbances to their natural motion or hindering their ability to play. Then, we designed an experiment involving dyads of violinists who performed the same musical piece under varying sensory feedback conditions combining auditory, visual, and haptic modalities.

The results confirm the role of visual feedback in violin duo performance and show that, although musicians are primarily trained to rely on auditory cues for synchronization, they draw heavily on visual cues, particularly in situations that challenge temporal alignment, such as the onset of pieces or in tasks involving temporal variability (48, 57–59). Specifically, the addition of visual feedback substantially improved kinematic coordination compared with its absence (AV versus A and AVH versus AH), and this effect was more pronounced among amateurs, who may not be accustomed to playing without visual contact from their partners; conversely, professionals can likely manage more effectively the loss of visual cues because of their proficiency. All participants, regardless of their expertise, consistently rated their performance higher when they could rely on visual feedback,

reflecting a higher familiarity and confidence with this sensory modality, which musicians are extensively trained to use.

Our results demonstrate that haptic feedback, despite being entirely unfamiliar, outperformed visual feedback in enhancing spatiotemporal coordination, thus challenging the primacy of visual cues in ensemble music performance and highlighting the potential of haptic feedback as a more effective modality. Previous research studies have characterized haptics as faster than vision, because it relies less heavily on cognitive processes (3), but also less spatially accurate (53, 54, 60). Yet, our results show that the superiority of haptics over vision is not limited to increased responsiveness (eliciting higher temporal coordination) but also includes higher movement accuracy, which improved spatial coordination. Because the bidirectional coupling was deliberately rendered as soft to moderate, the exoskeleton-mediated haptic torques acted as physical cues about the partner's movement rather than constraining forces. Therefore, we speculate that rendering embodied haptic cues directly at the joints elicited reflexive movement corrections toward shared spatial trajectories both in the task and joint space, which resulted in greater performance improvement compared with when musicians could rely on visual cues. This result is interesting considering that musicians consistently favored the visual feedback conditions and were not informed about the origin of the haptic cues, with most of them being unaware until the end of the experiment. Therefore, this finding suggests that haptic communication can modulate motor coordination implicitly, even when unfamiliar and not consciously perceived as preferable, supporting the idea that interpersonal coordination is underpinned by low-level sensory couplings (37, 61–63) and does not need to be explicit to influence the adaptation of motor behaviors between duo partners (14). Although spatiotemporal coordination was not affected by musical expertise, the effect of haptic feedback was modulated by it: Professionals appeared to benefit from haptic feedback compared with visual feedback even more than amateurs, despite their greater and consolidated experience with auditory-visual cues. This may be attributed to their greater ability to integrate subtle haptic information into their highly automatized motor routines (13, 64). Moreover, these findings support the idea that exoskeletons delivering haptic feedback can be exploited to surmount the ceiling effect that expert players may face when training in complex motor tasks such as music production (65).

Furthermore, combining auditory, visual, and haptic feedback consistently yielded the highest kinematic coordination, indicating that haptic cues do not interfere with other communication channels but rather augment them. Previous research hypothesized that interacting individuals can exploit haptic cues in combination with visual feedback (8) and internally optimize the weights of this sensory information to identify the optimal motor strategies toward the common goal (53), resulting in better performance (19, 66, 67). This supports the theory that multisensory integration is a valuable performance optimization strategy (68) and that individuals dynamically prioritize the most reliable sensory input available at any given time (61, 69). The multimodal condition likely facilitated redundancy and robustness in sensorimotor integration, thereby boosting synchronization regardless of expertise level.

The mere presence of the exoskeleton, when operated in transparent mode (A and AV), had different effects according to expertise: Amateurs outperformed their own nonexoskeleton conditions (BL and PT) in both spatial and temporal coordination, whereas professionals performed similarly. To rule out the possibility that

unintended torques were driving these effects, we compared the measured torques with the desired ones (zero in transparent mode) and show that the error remained below the just noticeable threshold for haptic stimulus. In other words, the improvements seen in amateurs may reflect a passive mechanical benefit, for instance, increased postural stability because of the device, rather than spurious torques. Conversely, professionals were able to accommodate the presence of the devices without notable changes in coordination or musical expressivity. Performing with the exoskeletons in transparent mode did not degrade the musical output, as demonstrated by the absence of changes in sound brightness across transparent and no-exoskeleton conditions. This demonstrates a key design requirement: We have developed complex, ecological exoskeletons that provide meaningful haptic feedback when engaged yet remain acoustically and kinematically invisible when disengaged.

Furthermore, a small increase in spectral centroid was observed among professionals in the haptic conditions compared with the transparent conditions. Although spectral centroid is widely used as a proxy for perceived brightness (55, 56) and has been linked to expert judgments of higher sound quality (70), the minimal effect size and the subjective nature of this timbral preference prevent us from interpreting this result as a haptic-related improvement. This result suggests that robot-mediated haptic feedback did not deteriorate sound production. Moreover, the audio results aligned with the kinematic analysis in capturing the coordination of dynamic changes, a key marker of musical coordination. Across all conditions, enhanced musical coordination was observed when haptic feedback was introduced (AH versus A and AVH versus AV), regardless of expertise. Because of the presence of the curtain positioned between the musicians to prevent visual contact, some conditions including and excluding visual feedback could not be directly compared in terms of acoustic measures (AVH versus A and AH), but the consistent pattern observed suggests that AVH would likely yield the highest degree of musical coordination. Overall, these results suggest that haptic communication enhanced coordination, not only kinematically but also acoustically, without compromising the sound quality. Nonetheless, results from the audio analysis should be interpreted with caution: Because of the naturalistic experimental setup, we could not fully eliminate the possibility of sound leakage between instruments, despite each violin being recorded with a dedicated microphone. Although this does not undermine the general trends observed, given that recording-level audio leakage is unlikely to explain the directionally consistent improvements found in the haptic conditions, it may nonetheless represent a potential source of confounding. All comparisons were restricted to matched acoustic setups (AH versus A with the curtain and AVH versus AV without the curtain), ensuring that any residual leakage was constant within each comparison.

To minimize adaptation effects across repeated measures, we included tempo as a washout factor by pseudorandomizing two values (72 and 100 bpm) across the experimental blocks and randomizing the order of sensory feedback conditions within each block. The results did not reveal any effect of tempo on the kinematic variables, indicating that interpersonal dynamics have a greater influence on kinematic coordination than the tempo. Although, in the analysis of dynamic musical alignment, we observed slightly higher coherence values at 100 bpm, particularly in the visual conditions, condition AV at 100 bpm did not outperform condition AVH at 72 bpm, indicating that the haptic condition consistently yielded stronger alignment,

even when the nonhaptic condition occurred at a more favorable tempo. This suggests that interpersonal dynamics, augmented by the robot-mediated haptic feedback, exert a stronger influence on interpersonal coordination than tempo alone. Additionally, we observed a modest improvement from BL to PT in temporal coordination among amateurs, but this result does not undermine the validity of our findings. This is because we counterbalanced the effects of sensory modalities and tempi by randomizing conditions so that any potential learning effect would not systematically carry over from one condition to another. Rather, it likely reflects growing familiarity with the task and with the partner's style, given that participants did not know each other before the experiment and had never performed together. Professionals, who are accustomed to playing with other unfamiliar partners, performed consistently throughout the session and did not show notable differences between nonexoskeleton conditions.

Our findings have theoretical and technological implications. From a neuroscientific perspective, they enrich the existing literature on the role of haptic feedback and the benefits of multisensory integration, but they do so by extending these insights to complex, real-life sensorimotor tasks. From a technological perspective, they open several possibilities for future research and applications. The improvements observed in this study are related to immediate dyadic performance rather than motor learning, and our results should be interpreted accordingly. In the broader literature, the question of whether haptic interaction supports long-term effects and motor learning remains open: Several studies reported learning benefits persisting after the haptic coupling was removed (14, 71–73), whereas others show no advantage over traditional training approaches (74–77). As discussed in a recent work (78), such inconsistencies likely arise from differences in robotic systems, task-specific constraints (limited tasks may be too simple to exhibit learning effects), and experimental designs (learning effects were mostly evaluated at the end of a single training session). Only a few studies have investigated learning over multiple training sessions and reported more consistent benefits from the haptic coupling (71, 79). These considerations underscore the need for longitudinal experiments to determine whether the benefits persist over time and support the formation of predictive models or merely act as a real-time correction mechanism. Clarifying this distinction is essential for understanding how such implicit sensory information is integrated during complex motor tasks and used to optimize motor learning. If these benefits were to be confirmed, then this paradigm could offer valuable opportunities for pedagogical and training applications. In music, bidirectional haptic feedback could be integrated into teaching and orchestral training, for instance, by pairing a teacher and a learner and allowing them to feel each other's movements in real time, facilitating a more precise, embodied understanding of the committed error (teacher) and the correct movement (learner) (35). Beyond a concert hall, this paradigm can likely be generalized to different contexts: In neurorehabilitation, haptic feedback delivered by exoskeletons could support motor relearning in patients by leveraging a more direct physical connection with the therapists (80). In such contexts, the robot-mediated interaction could be made asymmetric by tuning the viscoelastic torque field parameters so that the therapist (more-skilled partner) feels minimal forces, sufficient to haptically interpret the patient's movement intentions [as suggested in (32)], while the patient (less-skilled partner) receives stronger guidance. This is expected to minimize the perceived effort of the more-skilled partner while maximizing the motor

learning process of the less-skilled partner, as we demonstrated with dyads with different motor skills induced via visual noise (27). Nonetheless, these prospects must be approached with caution: All current evidence derives from healthy individuals, and it remains unclear how individuals with sensory or cognitive impairments would perceive the haptic cues and gain benefit from them. Targeted clinical studies will be needed to evaluate how such information is processed before a translational approach can be considered.

Despite the growing interest in physical human-robot-human interaction (20), reports of this paradigm applied to real-world contexts remain limited. As such, the exploratory nature of this work entails some limitations. Because of the gradual, nonpercussive nature of violin onsets and unavoidable microphone bleed in our recordings, we could not extract reliable inter-onset times, and, consequently, our analyses focused on more robust audio features, such as spectral centroid and RMS-based dynamic alignment. We also acknowledge that cognitive load was not formally measured, representing an additional limitation to be addressed in future work, and that effective joint performance of music is not solely determined by a high degree of spatio-temporal coordination among the players. Although musical duos are required to adhere to a shared metrical framework, the precise synchronization of note onsets and offsets is only one of the components of a successful performance. In some cases, it may be intentionally disregarded to achieve greater expressiveness (48). Future studies might also explore how the bidirectional haptic feedback influences the group flow (81, 82); how implicit haptic cues are processed by the central nervous system during complex sensorimotor tasks and integrated with auditory and visual cues; and to what extent this integration follows the multisensory weighting observed in simpler experimental contexts. In conclusion, this study explores the role of robot-mediated haptic feedback in joint musical performance and lays the groundwork for future interdisciplinary research that could offer valuable insights into and broaden our understanding of sensorimotor communication, joint action, music performance, human-robot interaction, and beyond.

MATERIALS AND METHODS

Exoskeletons

The exoskeletons used in this study feature one active DoF at the shoulder and one at the elbow, both exploiting series-elastic actuators for intrinsic compliance and safety during human-robot interaction. The active DoFs delivered haptic feedback along the elbow flexion-extension axis and a composite shoulder plane (flexion-extension and intra-extra rotation) (Fig. 1A), whereas a passive shoulder gravity unloader (PSGU) system supported shoulder flexion and extension and counterbalanced the weight of distal modules. The exoskeleton integrated a physical human-robot interface, passive DoFs, and adjustable features (Fig. 1B) that allowed precise alignment of human and robotic joints.

The control architecture followed a hierarchical structure comprising low-, middle-, and high-level layers (Fig. 1C). The low-level control layer implemented a closed-loop torque compensator, and each replica used joint-specific control architectures to achieve the desired behavior for every actuation unit. The middle-level control layer was specular for the exoskeletons, and it was based on a viscoelastic torque field τ_{des} described by the relation

$$\tau_{\text{des}} = K_v \cdot (\theta_{\text{des}} - \theta_{\text{meas}}) - B_v \cdot \omega_{\text{meas}} \quad (1)$$

where K_v and B_v are set as virtual stiffness and damping coefficients, respectively; θ_{des} and θ_{meas} are the desired and measured angles, respectively; and ω_{meas} is the estimated velocity. For the elbow module, the virtual spring stiffness was set for both modules to 2.7 N·m/rad, whereas the damping term was set to 0.23 N·m·s/rad, according to the maximum delivered torque and to ensure impedance loop stability. For the shoulder module, K_v was set to 14.3 N·m/rad and B_v was set to 0 N·m·s/rad following the same considerations. These stiffness values fall within the range typically used for soft or moderate elastic coupling in upper-limb dyadic interaction (24–27, 73, 83), because our goal was to provide informational haptic cues rather than physical guidance; therefore, the coefficients of the impedance control law were heuristically tuned through bench tests and pilot sessions with expert violin players to ensure that, even at the largest kinematic differences observed during bowing, the resulting peak torques (12 N·m for shoulder and 6 N·m for elbow) were perceivable yet did not interfere with natural violin-play kinematics.

The high-level control runs on the real-time processor and defines the human-robot-human interaction paradigm: In the no interaction (NI) configuration, the two exoskeletons are controlled in the so-called transparent mode (TM), in which the τ_{des} is set to 0 N·m and the users can move their arms freely with no haptic effect from the robot. In the bidirectional interaction (BI) configuration, both modules are controlled to create a virtual coupling between the users, as in Eqs. 2 and 3

$$\tau_{\text{des}}^{E1} = K_v \cdot (\theta_{\text{meas}}^{E2} - \theta_{\text{meas}}^{E1}) - B_v \cdot \omega_{\text{meas}}^{E1} \quad (2)$$

$$\tau_{\text{meas}}^{E2} = K_v \cdot (\theta_{\text{meas}}^{E1} - \theta_{\text{meas}}^{E2}) - B_v \cdot \omega_{\text{meas}}^{E2} \quad (3)$$

where $E1$ and $E2$ stand as identifiers for the exoskeleton replicas. Additional technical details regarding the mechanical design, electronics, and actuator specifications are provided in Supplementary Methods.

Participants and experimental protocol

The study was approved by the Ghent University ethics committee (ref. 2023–29) and conducted according to the Declaration of Helsinki. Informed consent was obtained from all participants before the study. We recruited 40 participants, including both amateur and professional violinists, and matched them into dyads on the basis of similarities in expertise and anthropometric measures, resulting in 20 dyads (10 professional and 10 amateur dyads). Additional details regarding the recruitment are provided in Supplementary Methods and table S1. Each dyad completed a single experimental session lasting ~3 hours at the Art Science Interaction Labs of Ghent University (Belgium). Participants were asked to wear an upper-body motion capture (MoCap) suit, which was configured with 24 markers according to the Qualisys Animation Marker Set, throughout the entire experiment (Fig. 2C). Minor adjustments were made to the marker positions to ensure consistency between recordings taken with and without the exoskeleton. In addition to the markers on the suit, four markers were placed on the violin and three on the bow.

Participants, who did not know each other before the experimental session, sat on separate chairs with their backs to the experimenters' workstation to prevent visual contact with them during the session, were provided with sheet music of a custom musical piece (Fig. 2B; see Supplementary Methods for details), and rehearsed together for 5 to 10 min. Once ready, they performed the piece twice

without the exoskeletons, establishing a preexperiment BL assessment. The tempo was set to 72 bpm and provided to the participants as a reference for the onset of the piece but was removed after four beats to avoid altering the evolution of the spontaneous temporal dynamics of the musicians. After the baseline, each participant donned a replica of the exoskeleton and underwent a familiarization phase with the device. During this phase, they experienced the different functioning modalities of the exoskeleton (transparent and haptic mode), blind to the characteristics of the specific control mode. Specifically, they performed different movements following one experimenter's instructions while another experimenter randomly changed the control mode. This was done to provide participants with an initial understanding of the type of interaction that they could be experiencing with the exoskeleton. After that, participants were asked to play the musical piece together while wearing the exoskeleton in different experimental conditions.

The main experiment consisted of six blocks, three at 72 bpm and three at 100 bpm. Each tempo was provided three times to ensure multiple repetitions of each sensory feedback condition and strengthen statistical robustness, and their alternation minimized short-term adaptation effects that could arise from repeated exposures at a single tempo. The tempo for the first block was selected randomly across dyads and then systematically alternated with the other one. In each block, participants performed the piece four times in randomized order under four sensory feedback conditions: AVH, AV, AH, and A feedback. In conditions A and AH, participants were separated by a black curtain to prevent visual contact (Fig. 2A) but could still hear each other well. As for the baseline measurements, participants were consistently instructed to perform the piece as a cohesive group, and the acoustic reference of the tempo was removed after four beats. After each condition, participants privately answered four questions on a tablet (see Supplementary Methods) while the setup was adjusted for the next condition, and, at the end of each block, a 3-min break was granted. After completing all six blocks, participants removed the exoskeletons and performed the piece twice more, serving as a PT assessment. Overall, participants performed the piece 28 times (Fig. 2D and movie S1).

Data acquisition and analyses

Motion capture data were collected at 120 Hz using a Qualisys motion capture system (Qualisys AB, Sweden) with 18 Qualisys 6+ infrared cameras and one RGB (red, green, blue) camera. Audio was recorded with a Y-pair of condenser microphones at 48 kHz and a bit depth of 24 bits. Exoskeleton data, namely, measured and desired joint angles and torques, were sampled at 100 Hz from the real-time loop and stored in the internal memories. To synchronize data from heterogeneous acquisition systems, we used Central Control software (84), an open-source software designed for real-time integration of multimodal experimental setups. MoCap and audio data were parsed in MATLAB (MathWorks, Natick, MA, USA) and processed with custom routines, whereas questionnaire data were collected via Qualtrics software (www.qualtrics.com) and processed in R version 4.3.2 (85) using the basic R environment and rstatix package (86).

Spatiotemporal coordination was assessed considering the movements of the end effectors of the human upper-limb kinematic chain in the task space (movement of the bow relative to the violin) and the joint angular trajectories of the right upper limb (shoulder, elbow, and wrist), which holds the bow. Specifically, we extracted from the motion capture data the coordinates of the instruments and calculated the position of each bow relative to its violin; then, we used PCA to calculate the principal movement components of the bow and estimated spatial

and temporal bow coordination. We adopted a similar approach to estimate the coordination at the joints: First, we calculated the upper-limb joint angles starting from the motion capture data; then, we used PLSC to extract the latent variables that maximized the covariance and calculated spatial and temporal joint coordination. Additional details on the calculation of the coordination metrics are provided in Supplementary Methods.

The characterization of sound production was based on the extraction of two key acoustic features, namely, spectral centroid and RMS amplitude. The spectral centroid represents the center of gravity of the sound spectrum and is used as a global descriptor of tonal brightness, whereas RMS amplitude provides an estimate of perceived brightness (additional details on the calculation of the acoustic features are provided in Supplementary Methods).

Statistical analysis

Data normality was assessed using the Shapiro-Wilk test. Given the unbalanced repeated-measures design (BL and PT assessments were repeated twice, and each feedback condition was repeated three times per tempo), mixed-effects models were used to investigate the effects of expertise, tempo, and condition while accounting for repeated observations within dyads by including dyad as a random effect.

For motion capture data, generalized linear mixed-effects models were fitted using a gamma distribution with a log link, as the data were nonnormally distributed and positively skewed, and this family minimized the Akaike information criterion. Fixed effects included expertise (two levels: amateurs and professionals), tempo (two levels: 72 and 100 bpm), condition (six levels: A, AV, AH, AVH, BL, and PT), and their two-way and three-way interactions. The model formula was specified as

$$y \sim \text{expertise} \times \text{tempo} \times \text{condition} + (1 | \text{dyad}) \quad (4)$$

For audio data, linear mixed-effects models were used, given that the distribution of the acoustic measure was approximately normal and did not show increasing variance with the mean. In this case, the response variable was log-transformed to stabilize residual variance. The fixed and random effects structure matched that of the motion capture models, with the exception that, for spectral centroid, individual participants instead of the dyads were used as random effects. DoFs and *P* values for fixed effects were computed using Kenward-Roger approximation via the lmerTest (87) package. Post hoc tests with Šidák correction for multiple comparisons were performed in case of significance.

Questionnaire data were analyzed using nonparametric tests because of their ordinal nature and nonnormal distribution: Wilcoxon signed-rank tests were used for paired comparisons, Mann-Whitney *U* tests for between-group comparisons, and Friedman tests for comparisons across multiple conditions. All statistical analyses were performed with IBM SPSS Statistics for Windows version 26.0 (88) and R version 4.3.2 (85) using a basic R environment, WaveletComp (89), lmerTest (87), and emmeans packages (90). For all tests, the significance level was $\alpha = 0.05$.

Supplementary Materials

The PDF file includes:

Supplementary Methods

Figs. S1 to S3

Tables S1 to S24

References (91–104)

Other Supplementary Material for this manuscript includes the following:

Movie S1

Data file S1

MDAR Reproducibility Checklist

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Competing interests: A.P., R.C., F.G., S.C., and N.V. are shareholders of IUVO S.r.l.; S.C. is a scientific adviser to IUVO S.r.l.; F.G. is a member of the board of directors of IUVO S.r.l.; N.V. was a scientific adviser to IUVO S.r.l. from July 2024 to July 2025 and a member of the board of directors of IUVO S.r.l. until March 2024. IUVO S.r.l. (Pontedera, Pisa, Italy) developed the shoulder module and owns the related intellectual property. N.V. is an author of the patent covering the spring embedded in the elbow actuator, which has been licensed to IUVO S.r.l. The other authors declare that they have no competing interests. **Data, code, and materials availability:** All data needed to support the conclusions of this manuscript are included in the

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